

## **THERMAL AND MECHANICAL MICROSPACECRAFT TECHNOLOGIES FOR DEEP SPACE SYSTEMS PROGRAM X2000 FUTURE DELIVERIS**

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### **Abstract**

Thermal and mechanical technologies are an important part of the Deep Space Systems Technology (DSST) Program X2000 Future Deliveries (FD) microspacecraft. A wide range of future space missions are expected to utilize the technologies and the architecture developed by DSST FD. These technologies, besides being small in physical size, make the tiny spacecraft robust and flexible. The DSST FD architecture is designed to be highly reliable and suitable for a wide range of missions such as planetary landers/orbiters/flybys, earth orbiters, cometary flybys/landers/sample returns, etc. Two of the key ideas used in the development of thermal and mechanical technologies and architectures are: 1) to include several of the thermal and mechanical functions in any given single spacecraft element and 2) the architecture be modular so that it can easily be adapted to any of the future missions.

One of the thermal architectures being explored for the DSST FD microspacecraft is the integrated thermal energy management of the complete spacecraft using a fluid loop. The robustness and the simplicity of the loop and the flexibility with which it can be integrated in the spacecraft have made it attractive for applications to DSST FD. Some of the thermal technologies to be developed as a part of this architecture are passive and active cooling loops, electrically variable emittance surfaces, miniature thermal switches, and specific high density electronic cooling technologies. In the mechanical area, multifunction architecture for the structural elements will be developed. The multifunction aspect is expected to substantially reduce the mass and volume of the spacecraft. Some of the technologies that will be developed are composite material panels incorporating electronics, cabling, and thermal elements in them.

The paper describes the current state of the technologies and progress to be made in the thermal and mechanical technologies and approaches for the DSST Future Deliveries microspacecraft.

## **INTRODUCTION:**

The application of "Faster, Better, and Cheaper" approach to NASA science missions in the 1990's has led to a significant increase in annual number of missions launched. It is expected that the NASA science community would greatly benefit if spacecraft were available quickly and cheaply to launch the science payloads on various missions. However, the spacecraft architecture, design, and fabrication practices that were used in the past have not been able to provide the needed features for the many of the newer science missions during the new Millenium. This has led to the current Deep Space Systems Technology (DSST) Program X2000 Future Deliveries effort to develop microspacecraft architectures based on advanced technologies that would result in smaller, more capable, and cheaper spacecraft.

The thermal and mechanical spacecraft technologies used in the past NASA missions have been more to accommodate the request of the other spacecraft subsystems and science. These technologies were perceived more as an afterthought than as the driving technologies to enable the spacecraft architecture. This has led to fewer revolutionary thermal and mechanical technologies being developed and implemented on the NASA spacecraft. The current need for smaller, quicker, and cheaper spacecraft has necessitated a vigorous investigation of thermal and mechanical technologies for the DSST Future Deliveries.

In the area of thermal and mechanical microspacecraft technologies, the efforts have been to reduce the size of the spacecraft and also to make them flexible and robust to be used in wide variety of missions. One of the key ideas for reducing the size is to include several functions in each of the thermal and mechanical elements. The other key idea to make the spacecraft flexible is to design it with modular elements that can be easily assembled to meet the thermal and mechanical requirements of any of the desired missions.

## **THERMAL TECHNOLOGIES:**

Present State of Thermal Technologies: The thermal technologies used in the planetary spacecraft built in the past for NASA have generally consisted of passive technologies. Typically these technologies were geared for larger spacecraft of the sizes in the 500 to 2500 kg range. The thermal technologies and hardware used on these spacecraft are: passive fixed radiators, multi-layer insulation blankets, mechanical louvers, heat pipes, heaters, thermostats, heat switches, thermal isolators etc. However, during the last five years there has been a greater interest in injecting advanced technologies to provide more robust and reliable thermal control on the spacecraft. Examples of this are the two-phase devices such as capillary pumped loops and loop heat pipes.

The advantages of passive thermal control technologies are that they have a long heritage of usage on spacecraft and are known to be very reliable. The high reliability

comes from the passive aspect of these technologies; there are fewer failure mechanisms that exist for passive hardware. Even any degradation in performance that occur in these technologies is generally more gradual than a total loss of functionality. These are the key advantages that made the spacecraft thermal design to be based on passive technologies in the past.

The use of completely passive thermal technologies on spacecraft has come with certain disadvantages. These disadvantages are the following:

- The passive thermal control designs are generally bulkier, both in volume and mass and are not generally robust for spacecraft operation away from the design point
- The design phase tends to be longer due to extensive analysis that is required
- System level thermal vacuum testing is very important for passive designs since a lot of uncertain parameters used in the analysis need to be verified
- Large temperature margins are used in the analysis to accommodate the uncertainty in the passive design
- The performance of the MLI on the spacecraft is generally verified only from the system level thermal vacuum test
- Any significant change in the design parameters such as power dissipated by the components requires significant design changes in thermal control
- Because of the passive nature, there are fewer things to control and any anomaly during flight is harder to deal with
- Since the passive technologies generally lend themselves to self correction, spacecraft need to be closely monitored during flight

**Need for new Thermal Technologies:** The trend in NASA planetary exploration has been to launch more deep space missions to more destinations in the coming years. This has required that the spacecraft mass, cost, design, and implementation cycle time be kept low so that the goals of NASA be met in the coming years. The Deep Space Systems Technology Future Deliveries program is aggressively pursuing advanced technologies to achieve these objectives. One of the products of this effort is the development of microspacecraft architecture.

As missions carry more variety of science packages and go to destinations with more diverse thermal environment, there is a strong need for thermal control technologies that are more adaptable to such missions. Unlike the thermal control architecture on the past spacecraft with their passive thermal technologies, the newer technologies need to provide more autonomous functions and also more easily adaptable to various spacecraft configurations and mission environment. Further, in order to achieve smaller-sized spacecraft, they need to be combined with other spacecraft components such as structural members in a multifunctional structure. The thermal architecture should have knowledge-based intelligent character to be able to learn and develop good operating strategies during flight. Such attributes would reduce the cost of missions operations for the future missions.

There are several new thermal technologies that are needed to develop the new thermal architecture. One such technology is the active single phase cooling loop using mechanical micro pumps. Another technology is passive cooling loops using two-phase miniature loop heat pipes. Electrically tunable optical property materials are important for providing autonomous functionality. Some of the other technologies are miniature heat switches, high-density electronic thermal control, thermal energy storage, etc.

#### DSST FUTURE DELIVERIES THERMAL ARCHITECTURE:

The DSST Future Deliveries thermal control architecture is based on thermal energy management and called the Microspacecraft Integrated Thermal Energy Management System. This architecture will allow the spacecraft thermal design to accommodate variation in the spacecraft configurations and the mission environments through tailoring of a single basic design to be used again and again for many missions. Such flexible designs are key to enabling faster and cheaper designs for future microspacecraft. A schematic of the proposed thermal architecture is shown in Figure 1.

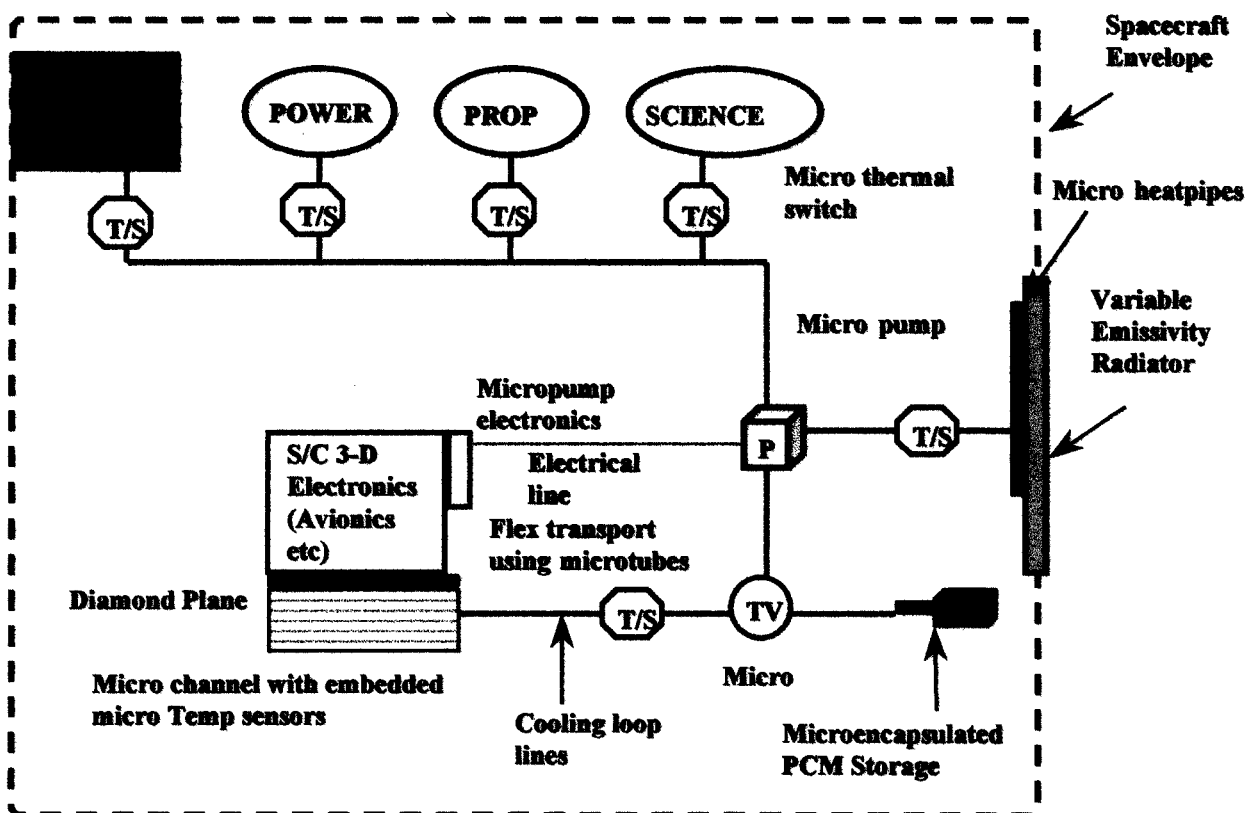


Figure 1. DSST Future Deliveries Microspacecraft Thermal architecture

Thermal control design for spacecraft is strongly influenced by the spacecraft configuration and mission thermal environment. Usually, the configurations vary significantly for each mission; a variety of spacecraft configurations are used in order to meet the needs of the individual missions. Furthermore, the mission thermal environment varies depending on whether the mission is to a planet, comet, sun etc. This variation in mission concepts and thermal environments indicates that major benefits would be derived from a flexible thermal control design concepts that would enable faster and less expensive design cycles. The Integrated Thermal Energy Management System encompasses variable emissivity surfaces to regulate the heat exchange between the spacecraft and its environment. Together with an internal heat loop, this combination provides the needed flexibility and accommodates low-cost overall design and implementation. Some of the other thermal technologies that will be used in this are the miniature thermal switches, phase change material thermal storage, and high-density electronic cooling technologies.

## **DESCRIPTION OF THE NEW TECHNOLOGIES:**

Miniature Single Phase Liquid Active Cooling Loops: Mechanically pumped single-phase liquid cooling loops are a robust thermal control technology for spacecraft thermal control applications. These have been used on space shuttle and on military fighter planes using various refrigerant liquids. However, they are not used on long duration deep space spacecraft. The Mars Pathfinder was the first spacecraft where a mechanically pumped single phase Refrigerant 11 loop was used for rejecting heat from an electronics shelf to an outside radiator (Reference 1). This system operated continuously for over seven months during Pathfinder's cruise to Mars. A life test system of the same ran for over 14,000 hours of operation at Jet Propulsion Laboratory before the test was stopped due to the cutoff of funds. The entire flight cooling system consisting of pumps, valves, accumulators, heat exchangers, radiators, working fluid, and motor electronics weighed 17 kg and transferred 150 Watts of heat and consumed 10 Watts of electrical power.

The active systems needed for the DSST FD are the ones using miniature pumps and the total system weighing one to two kilograms. Various mechanical pumps based on centrifugal and peristaltic designs are will be investigated. Some of the technologies in this field to be investigated are: MEMS based pumps and valves, piezo material activated pumps, and magnetically activated pumps.

Miniature loop heat pipes as cooling loops: Loop heat pipes (LHP) are based on capillary pumped two-phase devices and are being increasingly considered for spacecraft thermal control applications (Reference 2). The several thermal control functions an LHP provides in one element are heat transport, heat switching, and temperature control. The current state of LHPs are that they have been used on Russian spacecraft for over eight years and are currently planned on three NASA missions and on commercial communication satellites. Typically, the current LHPs weigh about 2 to 3 kg and have

about 1000 Watts of heat transfer capacity. The LHP technology needed for the DSST FD is expected to weigh less than 150 grams and transfer about 50 Watts.

Electrochromic materials: Variable emittance surfaces are an important thermal control element in the spacecraft thermal control design. The mechanical louver technology is the one that is currently being used on spacecraft. Typically these are bulky in volume and mass and are not easily scalable to smaller sizes. There has been some development in the electrochromic materials that would allow them to be used as variable emittance surfaces (Reference 3 and 4). The electrochromic materials are lighter and easily scalable to any size and also can effectively implemented in a multi-functional structure. This technology is being investigated under the Air Force and NASA Small Business Innovative Research programs. Solid state conducting polymer-based electrochromics can be made in flexible film less than 0.1 mm thick with an IR emittance modulation ratio of about 3. This technology will be actively investigated for DSST FD microspacecraft thermal control applications.

Miniature heat switches: A heat switch can be an effective tool in the spacecraft thermal control design. The current state of heat switch technology is not advanced enough for the microspacecraft thermal control applications. The present day heat switches are bulky and are not easily scalable to smaller sizes for microspacecraft applications. A 100 gram heat switch provides a thermal conductance of 0.7 W/C when on and an on/off ratio of about 100 (Reference 4). Currently there are lightweight heat switch concepts being investigated under the NASA Small Business Innovative Research program at Energy Science Laboratory Inc. aimed at microspacecraft and rovers. Novel material and designs are used to achieve significant miniaturization compared with conventional thermo-mechanical and gas-gap heat switches. A thermal performance of 0.2 W/C or better expected from a switch of weighing 1 gm.

High Density Electronic Cooling Technologies: The power densities of electronics used in spacecraft have been increasing significantly in the last several years. The thermal control technologies used in the electronics thermal design have not kept up with the advances made in the electronics. Some of the thermal control technologies that will investigated for microspacecraft electronic thermal control are the high thermal conductivity materials, thermoelectric cooling technologies, micro heat pipe devices, single phase liquid pumped cooling loops, and advanced packaging schemes.

## **MECHANICAL TECHNOLOGIES:**

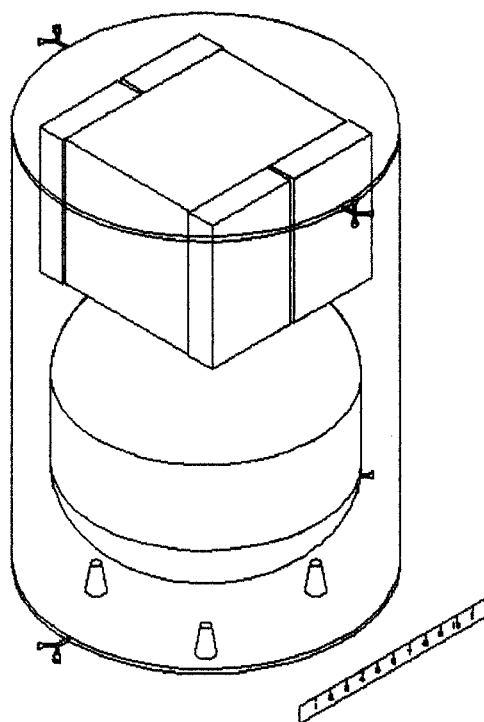
Present state of the Spacecraft Mechanical technologies: The spacecraft mechanical technologies used in the past have generally chosen for providing a reliable design to meet the spacecraft functional requirements. These technologies have generally focussed on providing a single function to each structural element such as carrying primary loads or to carry secondary loads of electronic packages. The various mechanical elements were mounted on separate structures and aluminum has been the main material used for

the structures. All this has led to the structure being one of the heavier subsystems on the spacecraft.

Newer mechanical technologies: As the flight components are reduced in the size, the sizes of the structural members are similarly reduced. In addition, the reduction in size and loads allows the structural design to take advantage of new technologies and new configurations that may not have been available when greater load bearing capabilities were required. The objective of the DSST Program is to demonstrate and bring new technology to flight readiness for future missions to utilize. In this spirit, the specific configuration of the actual flight model is not as important as the concepts it demonstrates.

#### **DSST FUTURE DELIVERIES MECHANICAL ARCHITECTURE:**

A candidate configuration for the Second Delivery of the DSST program is shown in Figure 2.



**Figure 2. DSST 2<sup>nd</sup> Delivery Microspacecraft Configuration**

The elements shown on this conceptual configuration are the propulsion tank, the optical communications assembly and the outer cylinder. In the Second Delivery, the

target size of the avionics will enable the components to be mounted on the optical communications cover. This eliminates electronics boxes and additional support structure. The cylindrical structure acts as the load bearing structure, protective cover for the propulsion tank, and support structure for solar cells. The configuration allows the spacecraft to be separated into two main components: 1) the cylinder and bottom plate along with the propulsion tank and 2) the top plate/radiator with the optical communications system and avionics. These two parts are designed to be separable to allow access to all areas after integration for rework.

The cylinder and bottom plate can be fabricated as a bonded composite structure, offering a weight reduction through use of a composite material and elimination of inserts and fasteners. Using a graphite composite structure typically results in a mass saving of approximately 40 percent over an aluminum structure. The disadvantage of a bonded composite structure is the difficulties in rework of either supported systems or structural members. In the reference configuration, full access to all subsystems is achievable with only one separate interface. In general, to fully take advantage of the use of generic multifunctional panels with the mass savings of a composite material, the panels must be replaceable. The structural attachments between panels will be examined to select or develop a method that is lightweight and reworkable.

Two approaches toward a reworkable bonded structure are to either design a joint with some combination of bonded sections and fasteners to minimize mass or to investigate adhesives that may be removed in some manner without damaging critical components

## **DESCRIPTION OF THE TECHNOLOGIES:**

The key mechanical microspacecraft technologies that are being investigated for DSST applications are multi-functional structures and panel bonding techniques.

**Multifunctional structures:** In the structural area, mass reduction can be realized through the use of multi-functional structures where the structural members with dual functions are maximized. The load bearing and protective functions are coupled with other functionality. In this way, the structural and mechanical roles become highly integrated with the other spacecraft systems, which leads to a more compact and lighter spacecraft.

One area in which mass savings can be achieved is by making the electronics boards function as structural members. Lockheed Martin Astronautics has demonstrated significant mass savings by eliminating traditional cabling on multifunctional panels. A multifunctional test panel fabricated by Lockheed Martin is currently flying on Deep Space 1 (Reference 7). The assembly concept used by Lockheed Martin is shown in Figure 3. The demonstration test panels fabricated have incorporated flex circuit patches, flex interconnects, integral thermal control, and standard connector interface with flex cabling.



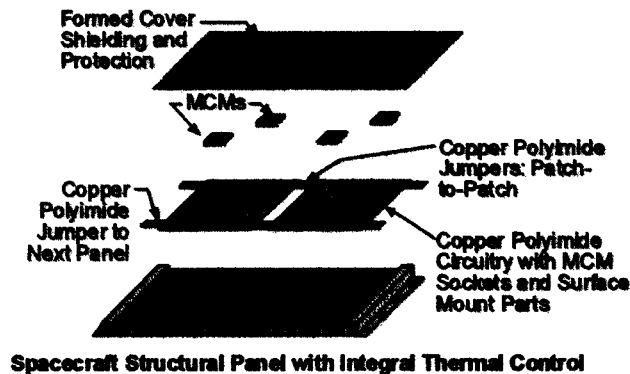


Figure 3. Lockheed Martin Multifunctional Structure Concept Incorporating Structure, Thermal, and Electrical Elements

The objective in the DSST FD mechanical task is to produce composite panels with a generic power and data bus on which the electronics are mounted directly. Development in the avionics area will enforce a uniform connection to the bus so that the feasibility of a generic panel becomes realizable. Once a generic panel can be built, they can be used as structural elements. This allows reduction in mass and along with a flexible thermal management system, greater flexibility in the configuration. In the Second Delivery, the approach used by Lockheed Martin will be reviewed while we continue to explore new cabling materials and mechanical and electrical attachments compatible with the selected support panel material and avionics developed

Maximizing the use of multifunctional structure deviates from the traditional spacecraft design approach because it moves away from delivering a primary structure on which the instruments and propulsion system are mounted. The structural elements will be integrated with the other subsystems to the extent that the interfaces between structural and other subsystems become more difficult to define. This integrated approach requires a much more coordinated effort through all phases of development.

**Panel Bonding Technology:** In the assembly of the microspacecraft, the way the panels are joined together is an important issue. The use of the bonding materials will substantially reduce the mass of the structure, however, it is harder to rework with the bonded joints if the panels have to be detached and reworked. In the DSST microspacecraft mechanical technologies area, the panel bonding technologies that would allow the panels to be easily disassembled and joined will be investigated.

## **IMPLEMENTATION OF THE THERMAL AND MECHANICAL TECHNOLOGIES ON THE DSST 2<sup>nd</sup> DELIVERY**

The several thermal and mechanical technologies described earlier will be developed in the DSST Future Deliveries. The DSST 2<sup>nd</sup> Delivery is an intermediate step, which is scheduled to be completed in 2003. For this delivery, only those technologies that have demonstrated their performance and can withstand space qualification will be included. In the thermal technologies, loop heat pipe and electrochromics based thermal energy management architecture will be implemented, the pump based cooling loops will be developed in the third delivery period. The mechanical technology area multifunctional composite panels with integrated electronic boards and cabling are planned to be included. The modular multifunctional panels will be developed in the third delivery period.

### **CONCLUSIONS:**

The injection of advanced thermal and mechanical technologies in future generation of microspacecraft is essential to achieve the faster, better, and cheaper spacecraft. These types of spacecraft are at the heart of the NASA's future planetary exploration. The recent developments in the thermal and mechanical technologies provide a good base for the choice of technologies that will enable microspacecraft architecture that will meet the NASA's goals. The DSST Future Deliveries architecture based on the thermal and mechanical microspacecraft technologies provides for the continuous evolution of future microspacecraft that efficiently integrates the latest technologies into the spacecraft.

### **AKNOWLEDGEMENTS:**

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